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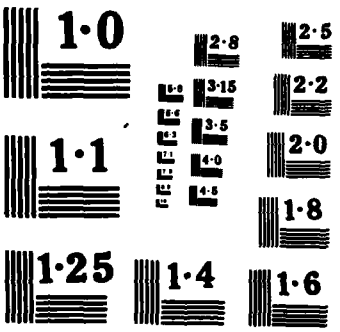
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 85-0373
6a. NAME OF PERFORMING ORGANIZATION: University of California, S. D. Inst. Pure & Appl. Phys. Sci. / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: USAF, AFSC, AFOSR/NP
6c. ADDRESS (City, State and ZIP Code): La Jolla, CA 92093	7b. ADDRESS (City, State and ZIP Code): NP/Bldg. 410, Bolling Air Force Base, Washington, D. C. 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR / 8b. OFFICE SYMBOL (If applicable): NP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR 83-0242
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS. — PROGRAM ELEMENT NO.: 61102F; PROJECT NO.: 2917/A6; TASK NO.: ; WORK UNIT NO.:
11. TITLE (Include Security Classification): Instrumentation for Particle-Beams Research Using Laser Excited Merging Beams	
12. PERSONAL AUTHOR(S): Neynaber, Roy H., Tang, Sheng Y.	
13a. TYPE OF REPORT: Final / 13b. TIME COVERED: FROM 6/25/83 TO 12/24/84	14. DATE OF REPORT (Yr., Mo., Day): 85/2/21 / 15. PAGE COUNT: 10
16. SUPPLEMENTARY NOTATION	

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Cross sections, molecular beams, reaction rates, ion-pair production, particle beams, laser excitation.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A summary of research performed under AFOSR Grant No. 83-0242 is given. The report is for the period 25 June 1983 - 24 December 1984. The review describes molecular-beam studies of ion-pair production and measurements of the fraction of excited Na atoms, f^*, in a composite beam of ground-state and excited Na atoms. The actual ion-pair production reactions studied are the following: $Na + Br \rightarrow Na^+ + Br^-$, $Na + Cl \rightarrow Na^+ + Cl^-$, $Na + I_2 \rightarrow Na^+ + I_2^-$, $Na(Na^*) + Na \rightarrow Na^+ + Na^-$, and $Li + Na \rightarrow Li^- + Na^+$. The reaction $Na + I_2 \rightarrow Na^+ + I_2^-$ was used to measure f^*. A value of about 6% was obtained. The work was performed using instrumentation provided by the grant.

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: ~~Roy H. Neynaber~~ Dr. Kelley	22b. TELEPHONE NUMBER (Include Area Code): (202) 767-4908 / 22c. OFFICE SYMBOL: NP

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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Research Objectives

Instrumentation purchased under the subject grant will be used to conduct particle-beam research of interest to the Air Force. Molecular beam techniques will be employed to study two-body reactions that will result in an intense, collimated beam of Li atoms at an energy of several hundred keV. Generating such a beam by charge transfer of a $Li^{(+)}$ beam is not efficient at this energy. It appears that it can most efficiently be produced by forming a $Li^{(-)}$ beam and stripping away valence electrons in a suitable gas. We plan to study reactions associated with the production of a $Li^{(-)}$ beam which is formed when a $Li^{(+)}$ beam interacts with a vapor of ground and excited (resonance state) Na atoms. One of the reactions (after $Li^{(+)}$ has been converted to Li) is $Li + Na^{*} \rightarrow Li^{(-)} + Na^{(+)}$. This will be examined by merging a Li beam with a beam of Na atoms excited with a single frequency dye laser. The instrumentation required to complete this study consists of some laser and optical components, some vacuum equipment, and a laboratory computer system for data acquisition and analysis. This apparatus will supplement as well as rejuvenate an existing merging-beam apparatus.

Status of the Research

The research accomplished on Grant AFOSR 83-0242 for the period 25 June 1983 - 24 December 1984 is cited below.

1. Absolute and relative cross sections were obtained for the ion-pair production process $Na + Br \rightarrow Na^{+} + Br^{-}$ in which the reactants and products are in the ground state. The studies were made by a merging-beams technique in a range of relative kinetic energy W of the reactants from the threshold of 1.78 eV to 500 eV. Agreement is excellent between the experimental results and calculations of Faist and Levine.

The purpose of conducting this experiment was three-fold. First, the basic physics of this ion-pair production process is interesting and particularly the threshold behavior, which is different from that of others

alkali-halogen systems previously measured. Second, the experiment would give us experience in studying this type of process. Such experience would be useful in investigating more complicated processes of ion-pair production involving excited and ground-state (g.s.) alkali atoms of special interest to the Air Force. Finally, the reaction could be used in measuring the fraction of excited Na in composite beams of excited and g.s. Na atoms. Later we see that for small fractions (i.e., $< 30\%$) another reaction was more suited to this purpose.

Our results of this study have been published.

2. A surface-ionization Li^+ source has been developed. A Li^+ beam from this source has been neutralized in a Na vapor cell resulting in a Li neutral beam. It was intended that such a beam be used for studies of Li interacting with an excited Na beam.

3. Our goal during the past year has been to prepare for studying the reaction $Li + Na^* \rightarrow Li^- + Na^+$, where Na^* represents excited Na in the $3p\ ^2P_{3/2}$ state. This reaction could eventually result in the production of intense Li^- beams and finally, through stripping, to equally intense Li neutral beams. The latter are of importance in Air Force applications.

One of the first requirements in achieving this goal was to produce a fast (several keV) Na^* beam. This was done by exciting a fast beam of g.s. ($3s\ ^2S_{1/2}$) Na atoms with a laser. The g.s. atom beam was produced by charge transferring Na^+ from a surface ionization source in a vapor of Na atoms. A single-frequency CW dye laser pumped by an Ar ion laser was used for the excitation. The laser was tuned to the Doppler shifted D_2 line (5890 Å) of Na. In fact, it was tuned for the hyperfine transition from $F = 2$ in the g.s. to $F = 3$ in the excited state.

An advantage of exciting a fast atom beam with a laser is that the Doppler width is considerably reduced from that obtained by exciting a thermal beam. In fact, for our 1300 K source temperature (corresponds to 0.11 eV) and an atomic beam energy of 5000 eV, a reduction of 2.4×10^{-3} spread in the velocity of the beam due to the source is calculated. The

resultant spread due to the source Δv_s = 230 cm/s, which is equivalent to a frequency change of $\Delta v_s/\lambda = 230 \div (5890 \times 10^{-8})$ = 3.9 MHz. This Doppler width is well within the 10 MHz natural linewidth of the Na-D_2 line as is the 1 MHz linewidth of the laser beam. Therefore, the laser was capable of exciting all of the g.s. F = 2 atoms in the beam and, in fact, saturating the transition. On this basis, it was calculated from the statistical weights of the hyperfine levels that 5/8 ÷ 2 = 5/16 or 31% of the atoms in the interaction region should be in the upper level.

An experiment was devised to measure $\Delta\nu$, the linewidth of the atomic beam. This width is a composite of $\Delta\nu_s$, a spread due to angular divergence $\Delta\nu_a$, a spread due to power broadening $\Delta\nu_p$, and the natural linewidth of the Na-D_2 line $\Delta\nu_n$. At 5000 eV, the $\Delta\nu$ is 45 MHz, which reduces to a spread of 30 MHz for the combined effects of $\Delta\nu_s$ and $\Delta\nu_a$ (after $\Delta\nu_p$ and $\Delta\nu_n$ were taken into account). The angular divergence of the experiment, or half angular spread, is about 5 milliradians, and computations indicate that a negligible fraction of the 30 MHz is contributed by this spread.

The significance of the above figures is the following. First, the measured linewidth of 45 MHz is quite large, and instead of exciting 31% of the atoms in the beam, the laser will roughly excited only $(\Delta\nu_c/\Delta\nu) \times 31 = (30/45)31 \approx 21\%$, where $\Delta\nu_c$ is a composite spread due to power and natural broadening. This fraction can be improved only by decreasing the velocity spread of atoms from the source since the other spreads are near their realizable minimums. It is not clear why the surface ionization source produces a spread of 30 MHz instead of its predicted 3.9 MHz, but presumably the trouble originates from resistivity in the fused, silica glass from which Na^+ emerges and a variable work function of the glass.

Actually, not even 21% excitation can be attained be attained because power broadening allows wing absorption to pump some of the atoms from the g.s. F = 2 level to the g.s. F = 1 level via the excited F = 2 level. These atoms cannot then be re-excited by the laser. We will see later that only about 6% excitation could be reached.

Because of the small percentage of excited atoms, beam-beam experiments would be very difficult, if not impossible, to conduct. We decided instead to confine our efforts to beam-gas methods. Elastic scattering is a bigger problem in beam-gas than in beam-beam experiments, but can be mollified by using larger collision energies, say in the range of several hundred to several thousand electron volts. This presents no problem for the Air Force study of producing negative ion beams since such beams have to be generated at fairly large energies in order to achieve sufficient intensity. Before such experiments could be done completely quantitatively, the actual fraction of excited atoms had to be measured. The next section describes how we accomplished that goal.

4. Actual measurements of f^*, the fraction of atoms in a beam excited by a laser, are rather rare in the literature. Generally, it is assumed that the laser saturates the excitation, and a calculated value of f^* is used. If a measurement is made, it is usually of the intensity of the fluorescence associated with the excitation. Rather than trying to measure photon intensities to determine f^* for our Na beam, we felt we could get a more accurate value through the use of a chemical reaction. We have used a similar technique in the past to determine the fraction of metastable atoms in a composite beam of excited and g. s. rare gas atoms. The trick is to find a reaction which proceeds with g. s. atoms but not with the excited atoms whose fraction is being measured. The f^* is then determined by measuring reaction products with the source of excitation on and off - in the present case, the laser. In our case of a composite beam of g. s. Na and Na^*, we concentrated on ion-pair producing beam-gas reactions, i. e., those reactions which produce a positive and a negative ion. (We had originally planned to use the beam-beam reaction $Na + Br \rightarrow Na^+ + Br^-$ for measuring f^*, but only 6% excited atoms obviated this approach.) Such considerations require that the sodium beam react with a gas which has a relatively large electron affinity (EA). Gases which were tried include O_2, NO_2, Br_2, and I_2. We settled on I_2, which has an EA = 1.72 eV. Ion pairs of Na^+ and I_2^-

are formed when the reactant covalent potential curve of g.s. Na and I_2 crosses the product ionic curve of Na^+ and I_2^-. The covalent curve of Na^* and I_2 crosses the Na^+ and I_2^- curve at such a large internuclear distance (and hence with negligible coupling) that no interaction and, hence, no I_2^- occurs. The f^* measured with this reaction was about 6%, as mentioned previously. We have published a paper on this technique. The first experiment we conducted using a Na^* beam is briefly described next.

5. We decided to investigate the ion-pair producing reaction $Na^* + Na \rightarrow Na^- + Na^+$ before the Li reaction because we had a cell for producing Na vapor and not one for Li. The vapor in such a cell is the gas that is reacted with the fast Na^* beam. Not only did we measure absolute and relative cross reactions Q^* for this process but also for $Na + Na \rightarrow Na^- + Na^+$, where all species are in the g.s. Figure 1 shows the results of some of these experiments. The graph shows Q^*/Q versus W, where Q^* and Q are the cross sections for ion-pair production for collisions of Na^*-Na and Na-Na, respectively. The results were obtained by measuring Na^- generated from the fast beam of atoms. It is clear from the figure that ion-pair production is greatly enhanced by exciting the Na, and we anticipate that the same will be true in the case of Li-Na^* collisions. We are preparing a paper for publication.

6. Another preparation we made for the Li-Na^* experiment was a study of the reaction $Li + Na \rightarrow Li^- + Na^+$, where all the species are in the g.s. Knowledge of this process is necessary because in the Li-Na^* study only a fraction of the Na beam will be excited. Most of it will be in the g.s., and the contribution to Li^- from the g.s. atoms must be known. The EA of Li and ionization potential of Na are such that the crossing radius of the covalent Na-Li and ionic Na^+-Li^- curves is 3.2 Å. This is relatively small and leads to a large coupling potential making it difficult to transfer ultimately from the covalent to the ionic curve. Thus, a small Q for ion-pair production is expected. Figure 2 is a plot of Q versus W, and indeed verifies the expectation. The results were obtained by measuring Li^- produced when a fast Li beam collides with a vapor of Na.

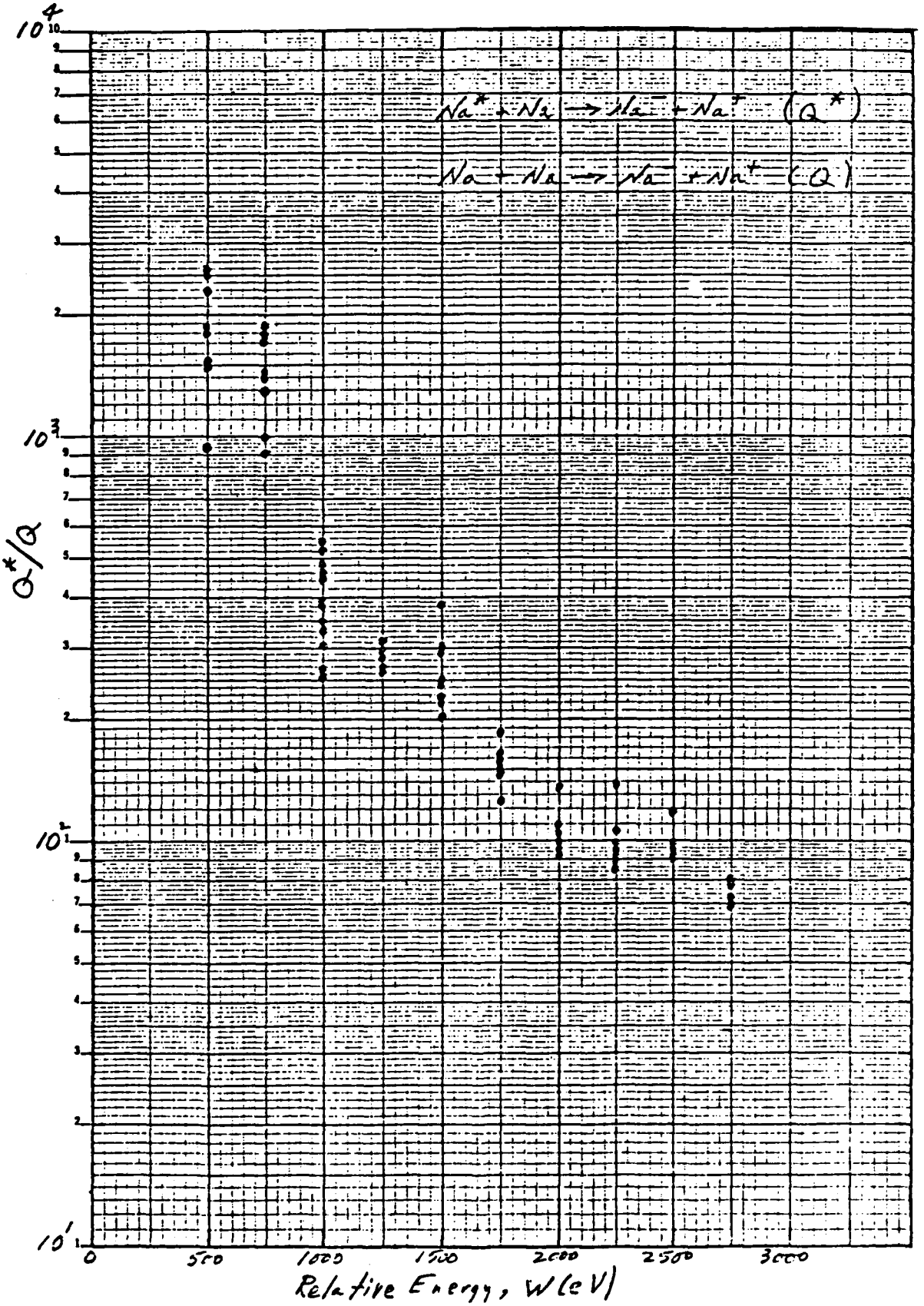
$Na^* + N_2 \rightarrow Na^- + Na^+$ (Q^*)
$Na + N_2 \rightarrow Na^- + Na^+$ (Q)
Q^*/Q
10^4
10^3
10^2
10^1
0
500
1000
1500
2000
2500
3000
Relative Energy, W (eV)

Figure 1

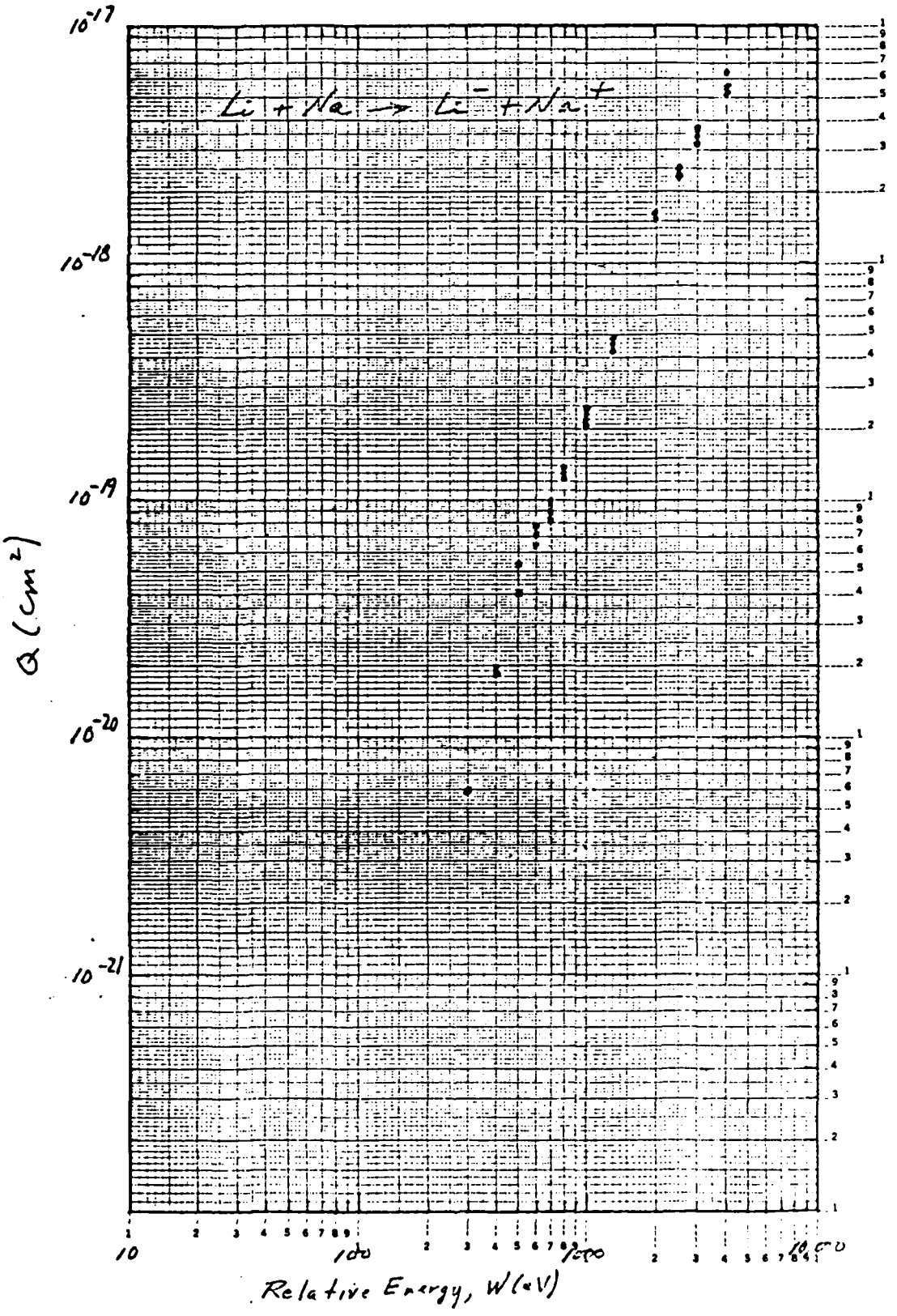
$Li + Na \rightarrow Li^- + Na^+$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
Q (cm²)
10
100
1000
Relative Energy, W(eV)

Figure 2

7. We have studied the ion-pair production process $Na + Cl \rightarrow Na^+ + Cl^-$. This is the second atomic alkali-halogen system that we have examined and only the fourth that has ever been experimentally studied and reported. We have made both absolute and relative cross-section measurements of the process over a range of relative energy from threshold to 10 eV. As for the Na-Br system, the theoretical predictions of Faist and Levine give good agreement with the data. We are preparing a paper for publication.

The reasons for studying this process are the same as for the Na-Br reaction. The Na-Cl reaction has actually been used to determine the fraction of excited Na in a composite vapor of excited and g.s. Na atoms. The excited atoms are raised to the resonance state by laser light. The technique and rationale for obtaining the fraction is much like that described previously for the measurement of f^* using the $Na-I_2$ reaction. In this case, though, the Na is stationary and the fast beam is Cl.

Financial Summary

Three equipment items were purchased under this grant. These items and their actual costs including tax and shipping are given below.

Item	Cost
Laser System	$ 50,478.11
Vacuum Pumping System	$ 8,505.75
Laboratory Computer System	$ 66,306.74
Total	$125,290.60

Publications

1. R. H. Neynaber and S. Y. Tang, "Ion-Pair Production in Collisions of Na and Br," J. Phys. B17, 3565 (1984).

2. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Fractional Determination of Laser Excited Atoms in Fast Na Beams," J. Phys. B18, L5 (1985).

3. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Ion-Pair Production in Collisions of Na and Cl," in preparation for submittal to J. Phys. B.

4. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Ion-Pair Production in Collisions of Na(3s ^{2}S) and Na(3p ^{2}P)," in preparation for submittal to J. Phys. B.

Participants

The participants in the research described above are Dr. R. H. Neynaber, Dr. S. Y. Tang, and Mr. D. P. Wang (graduate student).

Interactions

The Air Force Weapons Laboratory at Kirtland Air Force Base is interested in the production of Li beams and, thus, in any results associated with our forthcoming Li-Na* study, We keep in close touch with the laboratory and advise them of our results. Capt. G. McHarg of Advanced Concepts/NTYP is especially close to this problem and the person at AFWL with whom we communicate.

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